APPENDIX C
ENERGY TECHNOLOGY OPTIONS (ETO) MODEL

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INTRODUCTION

Determining which alternatives provide the most cost-effective means for a country to restrain the growth of carbon dioxide emissions entails a thorough economic evaluation of the available options. Economic evaluations of reducing carbon emissions have focused on taxation policies in the industrialized countries.[1] These assessments have sparked a debate over the level of taxes required to effectively restrain the growth of emissions, the extent to which "costless energy-efficiency improvements" will occur (Manne & Richels, 1991) and the cost of non-carbon-intensive (backstop) technologies. Recently, a study on Egypt (Blitzer et al., 1990) addressed the opportunities for using taxation measures to restrain CO_2 growth using a general equilibrium model of that economy and an analysis of Indonesia employed a system dynamics model to show that policies aimed at improving the technological base of the Indonesian economy can simultaneously increase the nation's GDP and curtail levels of carbon emissions. However, in most developing countries, where fiscal and technological resources are scarce, any effective emissions-abatement strategy must go beyond evaluating the impact of domestic policy changes on levels of carbon emissions. These efforts must identify the types of energy-supply and energy-use technologies needed to restrain the growth of carbon and must assess the capital investment and foreign exchange requirements needed to acquire less carbon-intensive technologies and fuels.

In order to address these issues, a model that facilitates evaluation of energy technology options (ETO) was developed. The model serves as an instrument for determining the least-cost options for providing energy services, evaluating the resulting levels of carbon dioxide associated with each option and estimating the impact of reducing emissions on the nation's capital and foreign exchange requirements.[2] Based on such an analysis, the model helps to identify policies and measures that would need to be implemented at both the national and international levels to make a major contribution to restraining the growth of carbon emissions.

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[1]See several papers in *The Energy Journal*, Special Issue on Global Warming, Vol. 12, No. 1, 1991.

[2]Economic Costs: The annualized costs of providing energy services, including capital, operation, and maintenance and fuel costs. Foreign Exchange Requirements: The costs of importing crude petroleum, its products and nautral gas. Investment: The funds invested in the energy sector in a particular year. These funds are mostly used to construct future energy facilities.

STRUCTURE OF THE ETO MODEL

ETO is a multisector linear-programming model in which the objective function being minimized is the economic cost to society of meeting the estimated demand for energy services (Table 1). The model can be run with alternative objective functions of minimizing the carbon emissions from the economy and minimizing the cost of production to the economy. The model is run for one target year, (e.g., 2005 or 2025) at a time.

The model evaluates energy-producing activities (e.g., crude oil and natural gas production, electricity generation from a wide range of resources, energy imports and exports, energy transportation) and links them with energy-using activities in the demand sectors through demand-supply balance equations. It also includes constraints on investment and foreign exchange as a fraction of an economy's gross domestic product (GDP). Each variable is also bounded so that no negative values are permitted.

Table 1. Multi-sector Linear Programming Model

Alternative objective functions:
1. Minimize the economic cost of providing energy services
2. Minimize the carbon emissions from the economy
3. Minimize the economic cost of production

Constraint sets:
1. Fuel balance equations
2. Demand-supply balance equations
3. Investment constraint
4. Foreign exchange constraint
5. Non-negativity bounds

The energy system may be represented by a set of 200 or more activities which together make up the total energy inputs into the economy. This set includes a range of different options for satisfying the energy requirements of the same end-use. For example, the model considers various options for providing lighting services in households, including kerosene, conventional light bulbs and fluorescent light bulbs. Figures 1 and 2 give a schematic representation of the sectoral options considered in an application of the model for India (Mongia et al., 1994).

We describe the supply and end-use options below as they are currently represented in the model. These can be easily modified by adding more options or deleting the ones that are not relevant.
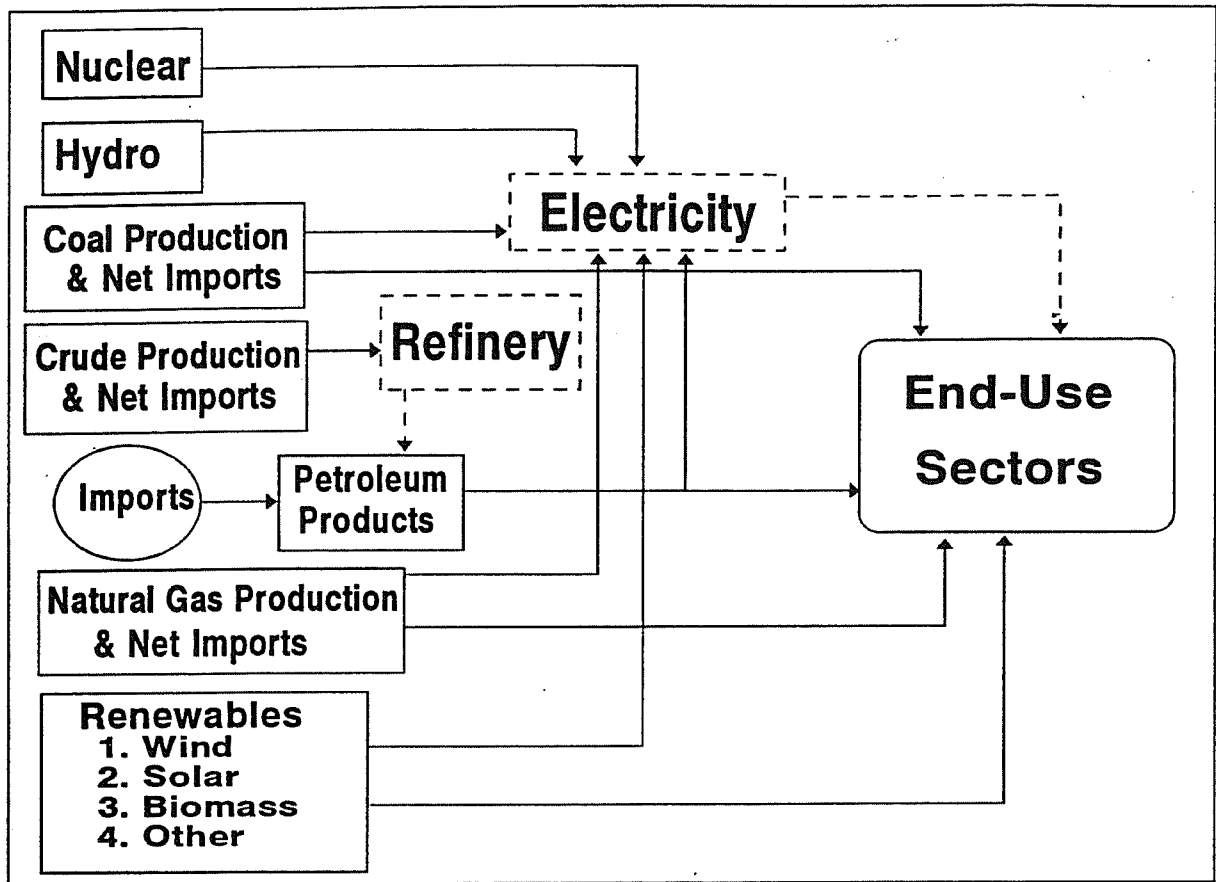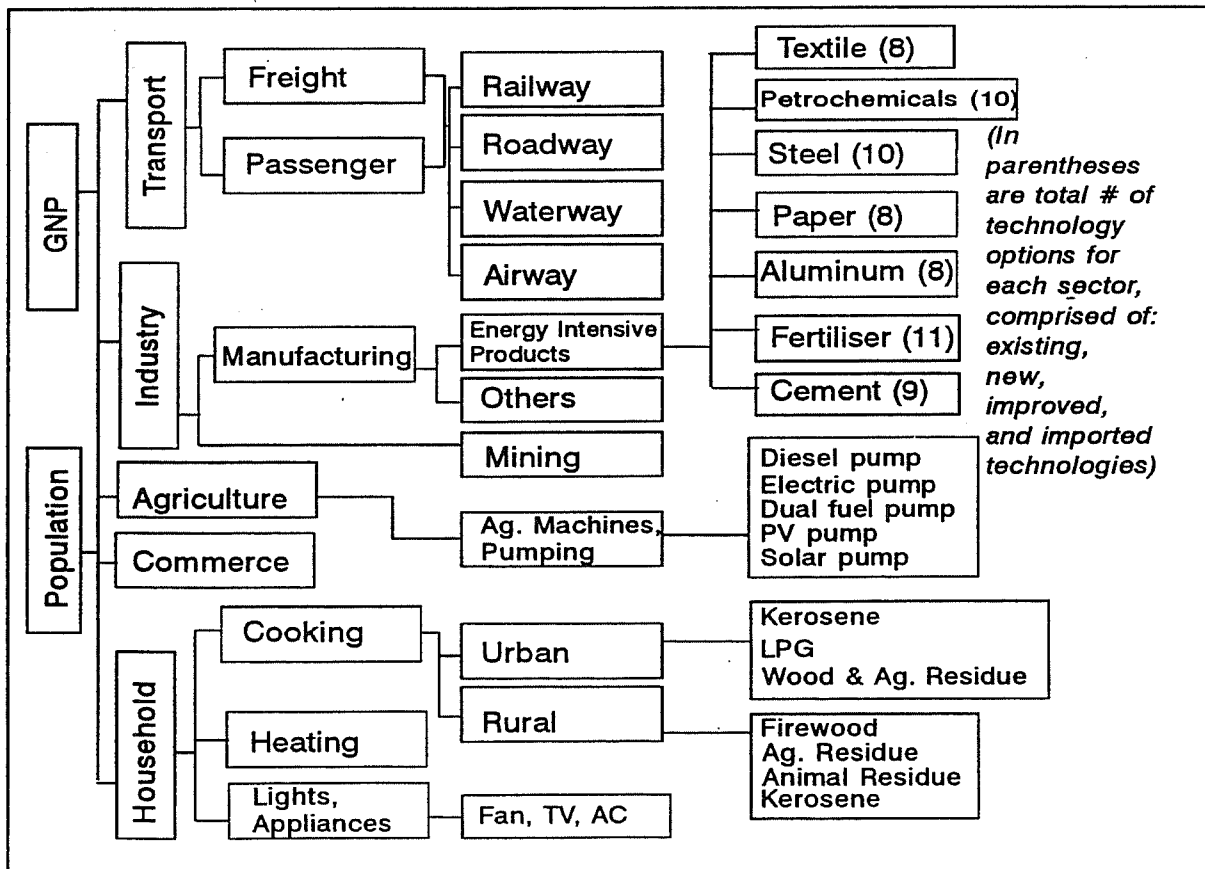
Figure C–1. Energy Supply System

Figure C–2. Sectoral Composition of Final Energy Demand

Energy Supply Options

The supply sources considered in ETO include conventional primary energy resources such as crude oil, natural gas, coal and petroleum products (e.g., naphtha, diesel, petrol, kerosene and jet·fuel), and non-conventional renewable supply options like wind, solar, biomass and nuclear power. The model takes into account the need for imports of a range of fossil fuels to augment domestic energy production. In the case of refinery products, the model considers both domestic end-use needs and the trade of petroleum products. For example, demand for one component of a refinery product can lead to the excess supply of another less desirable component, which then must be exported.

Each major supply option is represented separately. Several different technological options are identified for refining crude oil, all of which have different product yield coefficients, investment requirements and production costs. Similarly, the model examines four different options for coal production. These options fall into two broad categories, coal production through open-cast or underground mining. These are disaggregated further to represent existing options and those that require new investment funds. In the case of electricity generation, the model considers three broad categories of electricity generation from hydro resources, three from coal and one each from fuel oil, natural gas and nuclear energy sources. In order to keep the model simple and computationally manageable, supply options are not further disaggregated by engineering processes. This simplification does not significantly alter the results, since the costs and carbon emissions of options with different processes are similar.

Energy End-Use Options

The energy-using activities considered in the ETO model span all the major end-use sectors: agriculture, industry, transport, urban and rural residential, and commercial.

The model divides the industrial sector into generic electricity technologies and in terms of major energy-intensive industries (steel, cement, aluminum, petro-chemicals, paper, fertilizer and textiles). Each energy-intensive industry is divided into several different manufacturing processes. The energy-related options range from retrofitting techniques or simple energy-efficiency measures with small investments to green-field technology options with large investment requirements. (For example, Table 4-1 in Chapter 4 shows the alternative aluminum manufacturing processes included in the model.) For the other industries, seven generic electricity options are applied; these include a range of energy-efficiency options, such as improved belts, better motors and power factor correction.

The transport sector is disaggregated into a range of freight and passenger transport modes, spanning rail, road, coastal shipping and air travel. The primary options are electric and diesel traction for railways and petrol, diesel and renewable fuels for the various road modes (i.e., trucks, buses, cars and two wheelers).

The analysis of rural and urban households focuses on three major end-use activities: lighting, cooking and appliance use. For each end-use activity, the model works with the useful energy requirements to satisfy the given end use. The options considered range from the use of traditional fuels like biomass, in rural households to the use of liquid petroleum gas (LPG) and electric stoves in urban homes. For lighting, choices vary from kerosene and ordinary bulbs in rural

areas to fluorescent bulbs and specular reflectors in urban areas. In all, the model considers 19 urban and 12 rural end-use options for the household sector.

In the agricultural sector, the two major energy-using activities identified involve land preparation and water pumping, which depend on either diesel or electricity. In the case of agricultural pumping, the model considers a range of alternative fuel options as well, including biogas, photovoltaics, solar thermal and wind energy.

Approach

The energy service requirements for a future target year such as 2005 or 2025 are exogenous inputs to the model. These are estimated outside the model through an end-use analysis approach or through simple extrapolation of time trends or econometric methods. Given the requirements of satisfying these energy services, the model determines the lowest cost combination of options for meeting each particular service by evaluating the total costs incurred from the point of generation to the point of end use. The costs associated with each option take into account conversion efficiency at each step along the fuel chain. For example, in the case of lighting, each of the three options (kerosene, incandescent bulbs and fluorescent lamps) has a unit cost for providing a given level of useful energy (i.e., lumens), this cost incorporates the efficiency of that fuel for providing the energy service (e.g., kerosene has a very low efficiency for lighting compared to electricity). The model chooses the combination of options with the lowest unit cost.

With the inclusion of carbon constraints, the model chooses a different set of options to satisfy the same energy service.[3] For example, in the case of lighting, the model compares the costs and emissions levels of using kerosene with those associated with providing electricity at the margin. In this case, electricity would be preferred only when the unit cost and CO_2 emissions of the complete fuel chain for providing electricity were lower than for supplying kerosene.

Data Requirements

The model requires data on cost components -- capital, foreign exchange and operating cost -- of each activity represented in the model. The energy performance and carbon emissions associated with each activity also need to be included. Cost coefficients for each of the energy supply sources may be calculated using government publications, annual surveys of industries, statistics on national income, reports of the country's planning commission on the energy sector and annual reports of concerned ministries. These coefficients may be calculated for both production and transportation costs of coal, crude oil, natural gas, petroleum products and electricity transmission. For the calculation of yield coefficients from the various refining options, petroleum and natural gas statistics issued by relevant ministries and other government institutions may be used.

The model requires assumptions regarding the price of indigenous and imported crude oil, natural gas, coal and other primary fuels for the target year, and regarding the petroleum product margins to crude prices. The economic cost of domestic fuels is based on the cost of producing and transporting each fuel. The costs are expressed in constant currency for a given year, and a constant exchange rate is used throughout the analysis.

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[3]CO_2 emissions have to be estimated for each of the energy-using activities, as well as for electricity generation.

USING ETO TO ANALYZE SCENARIOS

The model may be used to analyze alternative scenarios of useful energy demand and socio-economic activity, as illustrated in the following section.

Table 2 describes the characteristics of three alternative scenarios. For each scenario, the mix of technology is determined so as to minimize the economic cost to society of meeting the estimated requirements for the identified energy services. In each case the model calculates the associated carbon emissions and requirements for capital and foreign exchange.

Table 2. Description of Scenarios		
Scenario	Carbon Constraint	Characteristics
Scenario 1	None	Energy efficiency of supply and demand technologies is either frozen at base-year levels or follows current trends.
Scenario 2	None	Efficient technologies permitted. Follows current trends for fuel switching.
Scenario 3		
Case 1	Yes	Estimates lowest carbon emissions consistent with meeting demand for energy services. Allows for further fuel switching and efficiency improvements.
Case 2	Yes	As above with greater reliance on renewables.

Scenario 1 allows changes in the efficiency of demand and supply technologies and fuel switching consistent with current trends. The strategy illustrated in this scenario is constrained only by the availability of indigenous and imported resources. Carbon emissions are not constrained.

Scenario 2 allows for more efficiency improvements in supply and demand technologies, and assumes fuel-switching policies which comply with current trends. The cost of providing energy services is lower than in Scenario 1, since many energy-efficiency improvements cost less than supply expansions.

The assumptions in Scenario 2 imply that the energy sector would operate in a manner so as to minimize the cost of providing energy services, which also lowers capital and foreign exchange requirements. Although this is a desirable scenario, the many barriers to achieving it are likely to prevent its full implementation.

In both cases of Scenario 3, carbon emissions are successively reduced until the model determines that the energy system is unable to satisfy the final demand for energy services and products. In the second case of Scenario 3, the same level of constrained carbon emissions is achieved primarily through increased use of renewables.

Example Results for India

This section describes the use of the ETO model for analysis of carbon emissions scenarios for India (Mongia et al., 1991). The scenarios correspond to those described in Table 2.

In Scenario 1, the efficiency improvements are frozen at the base-year level.[4] As shown in Table 3, carbon emissions increase faster than GDP because the demand for energy services rises rapidly, but no improvements in energy efficiency occur. The higher use of renewables and natural gas moderates the increase to a certain extent. Due to supply expansions, the capital and foreign exchange requirements increase disproportionately faster than GDP. Investment in the energy sector, as a percentage of GDP, increases from 4% in 1985 to almost 7% in 2005 and 2025. Similarly, foreign exchange requirements as a percentage of GDP increase from 1.9% in 1985 to 4.4% in 2005 and 2025. In each case, the sharp increase will require that financial resources be transferred to the energy sector away from other sectors, which will also clamor for more capital and foreign exchange.

In Scenario 2, efficiency improvements are permitted both on the demand and supply sides. The results show that, through appropriate policy changes, it is possible to reduce carbon dioxide emissions in India by as much as 50 million tons of carbon (13%) in 2005 and 250 million tons (27%) in 2025 compared to Scenario 1. These reductions can be achieved without any additional cost, because the marginal return from efficiency improvements is higher than their marginal cost.

Reduction in transmission and distribution losses, combined with additional improvements in end-use and power generation efficiencies, reduce the generation of electricity by 10% in 2005 and 32% in 2025 compared to Scenario 1. They also reduce the level of investment required for coal power plants and mines. Similarly, opting for efficient technologies (like improved pumping in agriculture, more efficient vehicles in transport and the use of petroleum products in industry) reduces the demand for the import and subsequent refining of crude oil.

The total cost of providing energy services declines by 13% in 2005 and by 23% in 2025 relative to Scenario 1. As a result of the substantial efficiency improvements, the investment and foreign exchange requirements decline considerably compared to Scenario 1. As a percentage of GDP, the investment in the energy sector increases more slowly than in Scenario 1.

The results of Scenario 3, Case 1, show that further potential exists to reduce carbon emissions relative to Scenario 2. While this scenario allows for further efficiency improvements, because Scenario 2 exhausts all of the cost-effective efficiency options, the further reduction of carbon emissions is achieved through switching to less carbon-intensive fossil fuels and renewables. These measures require either additional foreign exchange or investments. The percentage of the emissions reduction is higher in 2025 than in 2005, because the 40-year time span allows for the retirement of existing coal power plants, permits much higher levels of gas imports, and facilitates the greater use of renewable sources of energy.

Due to the higher utilization of imported gas, Scenario 3, Case 1, requires lower investment and higher foreign exchange requirements than Scenario 2. In Scenario 3, Case 2, the use of more renewables increases the investment and costs of providing energy services. Foreign exchange requirements decline, however, because renewables displace imported fuels.

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[4]A later paper (Mongia et al., 1994) describes results when the efficiency improvements are not frozen but allowed to change in Scenario 1.

Table 3. ETO Results for India Economic-Implications of Reducing Carbon Emissions Billion (1985 Rupees)			
	1985	**2005**	**2025**
GDP	2410	6400	16970
GDP/Capita	3200	5350	10000
SCENARIO 1			
Emissions	110	390	920
Cost	470	1340	4070
Investment	100	450	1160
Invest./GDP (%)	4.1	7.0	6.9
Foreign Exchange	45	280	750
FE/GDP (%)	1.9	4.4	4.4
SCENARIO 2			
Emissions	110	340	670
Cost	470	1170	3170
Investment	100	330	740
Invest./GDP (%)	4.1	5.1	4.4
Foreign Exchange	45	270	590
FE/GDP (%)	1.9	4.2	3.5
SCENARIO 3 CASE 1			
Emissions	110	280	520
Cost	470	1190	3430
Investment	100	290	665
Invest./GDP (%)	4.1	4.5	4.1
Foreign Exchange	45	310	950
FE/GDP (%)	1.9	4.8	5.6
CASE 2			
Emissions	110	280	520
Cost	470	1310	3640
Investment	100	400	970
Invest./GDP (%)	4.1	6.2	5.7
Foreign Exchange	45	290	560
FE/GDP (%)	1.9	4.5	3.3

Table 4 illustrates the increase in unit cost of conserved carbon (CCC) in Scenarios 1 through 3 as the amount of carbon saved rises. By conducting alternate runs of Scenario 2 and placing progressively tighter constraints on carbon emissions, the cost of conserving carbon at levels between those in Scenario 2 and 3 were determined. For example, the cost of conserved carbon is Rs. 0.2 per kilogram (kg) when emissions are reduced from 340 million to 300 million tons (Table 5). This figure rises to Rs. 0.6 with greater carbon savings in Scenario 3 (Case 1).

Costs decrease at first, because improving efficiency proves less costly than expanding the energy supply. Costs then increase as more expensive fuels are substituted. The increase in cost is modest in 2005, since the present allocation of fuels in the Indian economy is not economically efficient, and thus, the introduction of substitute fuels does not lead to radical increases in cost. The pattern is similar in 2025, but costs increase sharply to Rs. 5.1 per kilogram carbon as limited amounts of renewable energy are introduced.

Table 4. Unit Cost of Conserved Carbon (1985 Rs./kg)

	2005		2025	
	Carbon Emissions (Mtons)	CCC	Carbon Emissions (Mtons)	CCC
Scenario 1	390		910	
Scenario 2	340	-3.4	670	-3.6
	300	0.2	610	0.8
			580	1.0
			550	1.0
Scenario 3	280	0.6	520	5.1

Baseline scenario and incremental cost

The choice of a baseline is crucial to the estimation of incremental costs of a mitigation scenario. For example, as Table 5 illustrates, if the frozen-efficiency scenario (Scenario 1) is identified as the baseline scenario, the cost of achieving the target level of carbon emissions set in Scenario 3 is negative to the Indian economy. However, if the lowest cost scenario (Scenario 2) is assumed to be the baseline scenario, the carbon emissions goal embodied in Scenario 3 can only be achieved at positive cost. In all likelihood, the incremental cost will fall somewhere between those suggested in using Scenarios 1 or 2 as a baseline.

Table 5. Cost of Conserved Carbon (1985 Rs./kg) in Scenario 3 Relative to Different Base Scenarios

Base Scenario	2005	2025
Scenario 1	-1.4	-1.6
Scenario 2	0.3	1.8

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